PERFORMANCE EVALUATION OF CRUCIBLE AND ROTARY MELTING FURNACES EFFICIENCIES FOR ECONOMIC DEVELOPMENT

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ABSTRACT
An enclosure in which energy in a no thermal form is converted to heat especially such an enclosure in which heat is generated by a combustion of a suitable fuel is known as furnace. The two furnaces lined with fire clay refractory use diesel as their source of fuel. In this paper structure-operation and fuel type- fuel combustion approaches are used to determine the efficiencies of the two furnaces. The result shows that the efficiency values for crucible and rotary furnace are found to be.

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INTRODUCTION
Furnace is an enclosed chamber in which heat is produced to generate steam, destroy refuse, smelt or refine ores e.t.c. furnaces are characterized by the ability to generate large amount of heat energy sufficient the soften or melt hard objects such as metals. In any application, the interest in the furnace is not only in its heating or melting a work piece but also in how well it does so, the level of fuel economy, duration or operation as well as the level of quality of products. Furnaces can either be heating or melting furnace. (Pitts D.R & Sissom L.E (2006)
In melting applications, its requirement that the heating system generate as much heat energy as possible and that the refractory conserve as much heat energy as possible, the efficiency is considered as the extent to which a furnace satisfies these requirements. I heating furnaces, the essential requirement are that a furnace should be able to attain a specified temperature value, heat or cool at a specified rate and soak or hold the charge at a desired temperature for a specified time. The efficiency is therefore the extent to which a control can be exercised over these features. Although different types of furnaces exist, their components are essentially the same; these are the heating system and the refractory system both system work together to achieve successful heating or melting of desired work piece. Crucible and Rotary furnaces are the commonest fuel-fired furnaces found in most foundries in the third world countries. In this study, Rotary and Crucible (bale-out type) furnaces of melt capacities 100kg and 80kg respectively were considered. They both used diesel as source of fuel and were lined with fireclay refractory. In furnaces operations, it is very common to calculate efficiency values from heat transfer within the furnace without giving attention to the effect of the furnace structure and the nature of production operation which are peculiar to each furnace.

This study therefore investigates the efficiencies of the Crucible (bale-out type) and the Rotary furnace using two approaches. These are:

(i) The structure-operation method and

(ii) The fuel type and fuel combustion method.

METHODOLOGY

The way and manner the two furnaces were analyzed and their production operation analysis was carried. After all the analysis the two furnaces was compared to ascertain their performance.

Structure-Operation Method: this method was based on the analysis of furnace structure and the production operation. The structure analysis involves the number of openings, their location, and capacity for conserving heat energy. The production operation, on the other hand, involves a measures of how much heat an opening conserves depending on frequency of exposure to the outside environment, as well as the degree of quality of melt owing to some features of production operation. (Wilbur C.T & Wight D. A, 1984).The physical structure of both furnaces consist of the shell (steel outer casing) and the internal refractory lining (alumino sollicate). Other accessories are auxiliary to the furnace unit.

Energy point: A point in the structure framework of any of the two furnaces that is characterized with the ability to let out heat energy in any form (conduction, convention or radiation) is described as an Energy point (J.K Akintuwade & M.O. Adenye 2007) the occurrence of energy point may either be structurally inadvent or structurally intentional. Therefore, any openings found in the structure is the furnaces, inadvented or intentional, qualify as an energy point. Inadvented energy point is that point or opening that occurred in the final furnace structure without the intention of the designer e.g. Microscopic openings, as discontinuities in the weld beams, bolted joints, cracks and other miscellaneous structural flaws occasioned by fabrication processes. Intentional Energy points, on the other hand, are the openings which the designer deliberately introduced as a matter of necessity in the design. Such openings serves as outlets or inlets for various materials. The energy points identified in the two furnaces are shown below

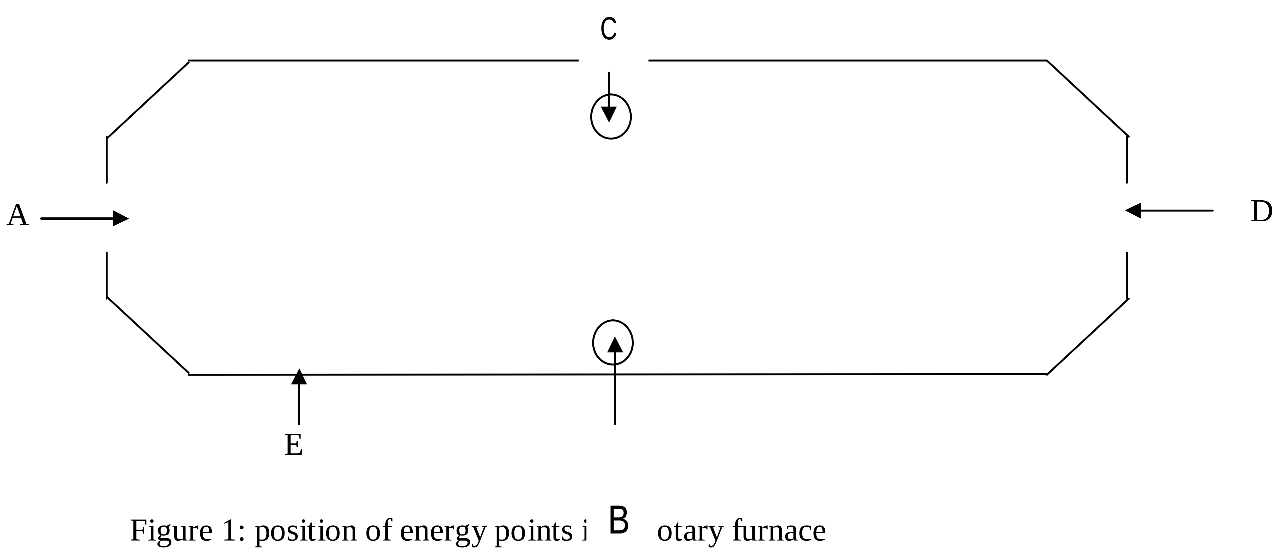

Figure 1: position of energy points i otary furnace

a. Burner end
b. Pouring spout
c. Emergency spout
d. Exhaust/ Charging end
e. Furnace body

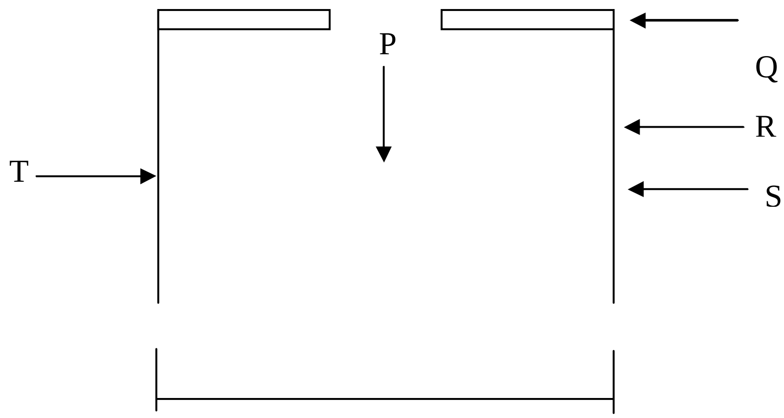

Fig 2: position of energy point in a crucible furnace
P: Exhaust end
Q : Lid opening
R: Furnace body
S: Burner end
T: Emergency spout

Function of Energy Points

A. (Burner end): this is an inlet opening for admitting heat energy into the furnace space through firing

B. (Pouring spout): This is an outlet opening for pouring molten metal from the furnace space into the molds

C. (Emergency spout): This an outlet opening serving as an alternative pouring spout if blockage occurs

D. (Exhaust/Charging end): This is an outlet opening for combustion products/introduction of change into the furnace space.

E. (Furnace body): This is an outlet opening inadvertently incorporated in the furnace structure.

Features of energy points

The furnaces of this study were studied and the following features were observed with reference to energy points for both furnaces. All intentional energy points are observed to occur in a definite number and each served a definite purpose; have definite size or dimension (the sizes would generally vary depending on furnace capacity); have specific location, and have definite energy potential (this is defined here as the capacity of energy point for conserving heat energy. In adverted energy points occurred in a random and relatively infinite number. However, for simplicity, the location of energy in the in adverted energy points was fixed as an arbitrary single points representative of all such points and the dimension was taken as microscopic for the purpose of references and evaluation.

Rotary Furnace

Mode 1: production Operation

E (Furnace Body) conserves the most heat and was ranked 4.5 on the Energy Scale. This is because it is an inadvertent energy point. It thus conserves the most heat. C (Emergency Spout) conserves nest to E. C. being an emergency opening may not be opened in Mode 1: Operation. However, in the event of blockage of B (Pouring Spout), C is opened and B remains blocked while tapping is done through C. in essence, same probability exists for the blockage of both B and C so that they were ranked on the same level 4.0. From observation of the production operations, B or C is not opened until the charge has melted, so both conserve heat better than A (Burner End) which is always opened throughout the operation. Consequently, A was ranked 3.5. D (Exhaust/Charging End) conserves nest to A and, of course, least. It should be noted that exhaust gases carry heat away from the hearth owing to an axial stream of air – current that issues from A, blows across the furnace bed and exits through D. D is thus ranked 2.5.

Mode II: Production Operation

In Mode II production operation, E (Furnace Body) still conserves the most heat and was ranked 4.5 on the Energy Scale. A (Burner End) conserves heat next to E and was ranked 4.0 on the scale. Both B (Pouring Spout) and C (Emergency Spout) conserve heat next to A and were ranked 3.5. They conserve heat more than A because on prolonged operation, tapping is done periodically and both the removal of hot melt and the attendant intermittent exposure of the combination chamber imply removal of considerable heat from the combustion chamber. B. and C were ranked on the same level because during Mode II operation, it is not unlikely that one of B and C might block. In such a situation, the other will be promptly opened to continue pouring for approximately the length of time it took the first to block and subsequently or alternately like that until the end of the production session. Ranking B and C on same level thus compensates for the equal likelihood of blockage and of exposure of the furnace space via either opening D (Exhaust/Charging Ends) ranks next and, of course, least. It does not immediately follow B and C on the Energy Scale for the same reason given in the case of Mode I Operation. D was rated 2.5.

Crucible Furnace

Mode 1: Production Operation

R (Furnace Body) conserves heat best and was ranked 4.5 on the Energy Scale. Both Q (Lid Opening) and T (Emergency Opening) conserves as much heat as R and were ranked on same level on the Scale. In a mode 1 operation, both Q and T act as inadvertent energy points.

Since both would nominally not be opened in this mode, rigid blockage is provided at both sites. At Q, the lid (with its refractory lining) fits well into the cylindrical body shell while at T the opening is tightly shut with no anticipation of opening. The resulting effect is that both Q and T conserve maximally – as much as R.. (Burner End) conserves heat next to R, Q and T, and was ranked 4.0 on the Energy Scale. Loss of heat at S is essentially due to radiation. P (Exhaust End) conserves heat next to S and was ranked 3.0. At P, heat is lost mainly by convectional heat flow. The quality of heat loss is substantial due to the high enthalpy of waste gases so that P jumped a step on the Energy Scale. This is due to the peculiar pattern of convectional heat flow in the crucible as against the rotary. During firing, the input heat is whirled all around the crucible pot within the hearth by the driving air – current thereby experiencing a circumferential circulation at the hearth before exiting through P.

Mode II: production Operation

R (Furnace Body) conserves the most heat and was ranked 4.5 on the Energy Scale. T (Emergency Spout) conserved heat next to R and was ranked 4.0. In this operation, spills are envisaged and are, in fact, almost inevitable. A spill that is drained through T is tantamount to removal of heat energy from the furnace space.

S. (Burner End) conserves heat next to T and was ranked 3.5 on the Energy Scale. S is an inlet opening that admits vaporized fuel into the combustion chamber. In practice however, the air-fuel volatile mixture produced by the burner is ignited at the mouth of the furnace so that some heat is lost by radiation from the open flames. O (Exhaust End) converses heat next to S and was ranked 3.0. in Mode II operation, the enthalpy of the gasses in the furnace chamber is higher. The exhausts coming forth through P thus carry a substantial amount of heat so that the potential of P is less than that of S.

Q (Lid Opening) conserves heat next to P and, of course, least. It was anked 2.0 on the scale. Q is an outlet opening subject to incessant opening for melt discharge (i.e. removal of crucible pot) and charging. Since the lid has the same diameter as the shell, on each opening of the lid, so much heat is lost by radiation and conventional flow that Q does not rank immediately after P but jumps a step on the Energy Scale.

A tabular summary of these analyses is provided in Tables 3 and 4.

Table 3: Average Potential and Efficiency for Rotary Furnace

MODE I		**MODE II**	
Energy Point	**Energy Potential**	**Energy Point**	**Energy Potential**
E	4.5	E	4.5
C	4.0	A	4.0
B	4.0	C	3.5
A	3.5	B	3.5
D	2.5	D	2.5

Overall Potential	18.5		18
Average Potential	3.7		3.6
Efficiency	74%		72%

Table 4: Average Potential and Efficiency for Crucible Furnace

MODE I		**MODE II**	
Energy Point	**Energy Potential**	**Energy Point**	**Energy Potential**
R	4.5	R	4.5
Q	4.5	T	4.0
T	4.5	S	3.5
S	4.0	P	3.0
p	3.0	Q	2.0

Overall Potential	20.5		17
Average Potential	4.1		3.4
Efficiency	82%		68%

Method II: Fuel Type and Fuel combustion

Analysis of combusting fuel

The following analysis holds for both furnaces since they both use diesel oil. Diesel is a distillate fuel oil of lower volatility and consists mainly of $C_{12}H_{26}$ to a composition of 98.5%; other constituents are 1% S, 0.25% N, and 0.25% O_2 (2). Hydrocarbons undergo combustion according to the general equation:

$$C.H.+[x+\frac{2}{1}]0_2 \rightarrow [x]CO_2 + [⅔]H_20 \qquad (1)$$

Thus Combustion equation for diesel is:

$$C_{12}H_{26} + 18.5\ O_2 \rightarrow 12CO_2 + 13H_2O \qquad (2)$$

In mass (kg) units

$$170\ C_{12}H_{26}+592\ O_2 \rightarrow 528CO_2+ 234\ H_2O \qquad (3)$$

$$C_{12}H_{26} + 3.482\ O_2 \rightarrow 3.106\ O_2 + 1.377\ H_2O \qquad (4)$$

The waste gases are taken to be nitrogen from the supplied air, carbon dioxide and water. The percentage by volume of each is obtained to be 73.68%, 12.63% and 13.69% respectively. The mean specific heats are 1.3683 KJ/(m^3.^oC) respectively at an average temperature of 800^0C from the Tables of Average Specific Heats of Air and Gases (Krivandin (1980). The average temperature of the waste gases exiting the furnace was taken as the average of the ambient temperature, 25^0C, and the maximum temperature obtained from combustion of diesel in the rotary furnace, 1510^0C [3]. Therefore, the mean specific heat of the waste gases, C_{wg}, is1.5072KJ/(m^3.^oC. the calorific value of diesel is given as 45 357LJ/kg[4].

Thermal Distribution of the Combustion Energy

Analysis of heat transfer in the combustion chamber of both furnaces would give the effectiveness of fuel combustion and the extent of heat lost to waste gases. From these, efficiency based on fuel type and fuel combustion can be calculated. These may then be compared with values obtained from structure operation (section 2.1) estimations to arrive at a value representative of the general efficiency of both furnaces under actual conditions of production operation.. The various heat items are computed below for the rotary and the crucible furnaces. According to Oyelami et al (2003), The total time of operation of each furnace comprises the time taken to melt the charge. For both furnaces the preheating time was 50 min. the time of melt for the rotary was 90 min and the fuel flow rate (B_r) is 21.05kg/h while that of the crucible is 70 minutes with a fuel flow rate (B_c) of 17 kg/h. thus, the total time of operation of the rotary (T_r) and the crucible (T_c) are 2.3h and 2.0h respectively.

The heat introduced into each of the furnaces was calculated from the chemical heat of fuel combustion. Q_1, given by (B,QT,) for the rotary furnace or (B_cQT_c) for the crucible furnace, where Q is the gross calorific value of fuel, 45 357 KJ/kg. The heat transported out of the finance space are (i) the heat lost with waste gasses, Q_2, given by (B_r V_{wg} C_{wg} I_a T_r is the volume of waste gasses produced from combustion, 12.329 m^3/kg of fuel; C_{wg} is the mean specific heat of waste gasses at t_a, kj/m^3.^oC); t_a is the average temperature of waste gases, 800^oC. Note that B_r and T_r are the rotary are B_c and T_c for the crucible, (ii) Heat lost by conduction maximum (1510_oC) and the initial (25_oC) temperatures of the lining; S_r and S_r are the measured average thicknesses of the lining and the shell respectively, they are 0.110m and 0.005m respectively for the rotary and 0.200m and 0.005m respectively for the crucible; a is the coefficient of heat transfer from the lining to air, 19.8W (m^2.^oG); K_r and K_r are respectively thermal conductivities of lining (1.37) W/(M^2 ^oC)) and steel shell (54 W(M^2 ^oG)). [3.6]. and (iii) heat lost by radiation through the openings. Q (winkle M. V. (2002), given by (C^o $(T/100)^4$ A $_r$D T,) where Co is the emissivity of a black body, 5.768 W/(m^2.k^{-1})

and Φ is the diaphragming coefficient, 0.7 (1): A is the surface area, m^2 of the open doors (Exhaust/Changing and (0.06 m) and Bumer end (0.05 m)) (obtained from measurement); T is the average temperature in the funance space which is equivalent to t_a, (800°C or 1073K). Therefore, the useful heat available for the change, Q (Adewoye O.O (2004) r in each case is (Qr (Q_2 + Q_3 + Q_4)). The results of all these calculations are shown in Table 5.

Table 5: analysis of heat in the combustion chambers of the furnaces (as calculated in section 2.2.2)

	Rotary Furnace	Crucible Furnace
Q1 (KJ)	2 195 959	1 542 138
Q2 (KJ)	719 728	505 438
Q3 (KJ)	26 095	15 108
Q4 (KJ)	2 360	1 478
Q5 (KJ)	1 447 776	1 020 114

Q1 - Chemical heat of fuel combustion
Q2 - Heat lost with waste gases
Q3 - Heat lost by conduction through the lining
Q4 - Heat lost by radiation through the openings
Q5 - Useful available for the charge.

RESULTS

The results are presented in Tables 3, 4 and 5.

In the rotary furnace, the various heat items have the following percentages; Q_1 (100%), Q_1 (33%), Q_3 (1.2%), Q_4 (0.11%(, Q_3 (85.7%).

In the crucible furnace, the percentages of the various heat items are: Q_1 (100%), Q_2 (33%), Q_3 (1%), Q_4 (0.1%), Q_5 (65.9%).

For both furnaces the efficiency based on fuel type and fuel combustion was calculated as the percentage heat considered if the waste gases were considered as the main source of heat loss. The value is: (100-33) = 67% in the two cases. Other sources of heat loss are negligible and may not be regarded as having a significant effect on furnace efficiency.

DISCUSSION

Comparing the efficiency values obtained from the fuel and fuel combustion method (67%) with that obtained from structure – operation method in section2.1 (Rotary: 74% Model 1 and 72% Mode II; Crucible: 82% Mode 1 and 68% Mode II), the efficiency values for Mode II production operation are more comparable. For the crucible furnace Mode II efficiency is 68%. This value is very close to 67% obtained from structure –operation. Mode II efficiency for the rotary is 72% and it is considerably higher than 67%. It should be noted that the efficiency obtained from fuel and fuel combustion method was based on fuel combustion and heat lost with waste gases which did not take into consideration the rate of opening and closing of openings. From structural analysis and production operation however the rotary furnace has a better performance due to its ease of operation, homogeneity of melt, uniformity of firing and effective heat transfer to the change. It can thus be concluded that 72% efficiency is more realistic for a rotary furnace.

Efficiency calculation based on structure – operation has the following features:

- Estimation of efficiency was based on average Energy Potential – a measure of capacity of energy points to conserve heat derived from observation of the production operation of both furnace.
- The efficiencies are not the same for the two furnaces (unlike in the case of fuel and fuel combustion), This is due to the different designs and production operation of both furnaces.

Efficiency calculation based on fuel and fuel combustion has the following features:

- Estimation of efficiency was based on the heat lost with combustion products (waste gases mainly, being the major source of heat loss).
- The efficiency is the same since both furnaces use diesel and the fundamental mechanism of combustion is the same.
- Heat carried with waste gases was used with no consideration for the rate of loss and degree of exposure of the combustion chamber.

CONCLUSION

Mode II production operation is the closest to the general industrial operation of both rotary and crucible furnaces encountered in real life productions. The efficiencies of the crucible and rotary furnaces based on structure – operation are 68% and 72% respectively. The general industrial operation of both furnaces should be regarded as close to Mode II operation. The efficiency for both furnaces based on fuel type and fuel combustion is 67%. Both furnaces have the same efficiency when the same type of fuel (diesel) is used since the fundamental mechanism of fuel combustion is the same in both furnaces. In both methods, the efficiencies obtained are quite comparable in the case of the crucible, whereas for the rotary they are not. Considering the production operation of both furnaces, the rotary is generally assessed to be more efficient than the crucible in terms of case of operation, homogeneity of the melt uniformity of firing and effective transfer of heat to the charge. Therefore, the efficiency of the rotary furnace obtained from structure – operation (72% is more realistic. The fuel type is a factor which may effect efficiency of both furnaces. This is because parameters such as amount of heat generated and impurity (type and quantity) that will be present in the melt are determined by the fuel. The more the heat generated the better the efficiency and the less the impurity the better the efficiency. Efficiency values obtained from Structure-Operation (Mode II) is recommended for the functional assessment of both furnaces. This is because this approach takes into consideration the structure, modes of production operation, and the capacity of the openings for conserving heat energy during each mode of operation. This approach thus provides the efficiency from factors which are peculiar to each furnace.

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